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Separation of Metals in Wastewater Sludge by Centrifugal Classification

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16. ABSTRACT Municipal wastewater sludges frequently contain undesirably high concentrations of heavy metals and/or organic pollutants which interfere with beneficial use of sludge on farmland and with some disposal practices such as ocean disposal. Centrifugal classification is a low cost procedure that has been demonstrated in this study to concentrate contaminants into the centrate stream, thus reducing the contaminants in the centrifuge cake and upgrading it for beneficial use.

Experiments with a small solid-bowl continuous decanter centrifuge were conducted to show the effects of machine and process variables (e.g., centrifuge speed, flow rate) on separation of heavy metals. The separations achieved were correlated by a recovery factor, f_r, where $f_r = x_w/x_c$. The terms x_w and x_c refer to concentrations of a component in the solids in the centrate (x_w) and the cake (x_c). The value of f_r was found to be relatively independent of the fraction of the feed solids removed as cake. Values of f_r were highest at high centrifuge speeds and high volumetric input rates. Recovery factors varied from day to day, no doubt as a result of changes in the sludge. Results from a full-scale installation at a Los Angeles County plant showed similar recovery factors, differing in some details. Examination of three years of Los Angeles operational data showed consistent separation with no marked trends. Average recovery factors (f_r) for cadmium for three successive years were 3.8, 3.7, and 3.2 at cake recoveries of about 40 percent. Los Angeles data also showed substantial concentration of organic pollutants into the centrate solids.

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Separation of Metals in Wastewater Sludge by Centrifugal Classification

Data for centrifugal classification can be suitably correlated by an easily correlated recovery factor, which can be calculated from a single replicated data point.

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Municipal wastewater treatment and many industrial processes produce aqueous sludges as waste products. Frequently, the principal components of these sludges are innocuous metal hydroxides or organic substances contaminated with a small amount of toxic or otherwise undesirable substances. Municipal wastewater sludge is a good example. Not considering its content of pathogenic organisms, whose impact can be reduced by proper disposal procedures, it primarily consists of human feces, paper fiber, laundry residues, food residues from garbage grinders, with varying quantities of road dirt and industrial wastes. The great bulk of the solid content is harmless or beneficial; toxic contaminants are generally present only in trace amounts. There would be substantial benefit if these trace substances could be removed economically. Extraction with organic solvents or mineral acids is effective in removing toxic organic or inorganic contaminants. However, these procedures approximately double the cost of sludge treatment and disposal [*1*, *2*], and so have not found any substantial use in upgrading municipal wastewater sludge to constructive use.

In their work at Lake Tahoe, California, with sludge produced in upgrading secondary effluent by lime treatment, Evans *et al.* [3] discovered that a solid-bowl continuous decanter centrifuge with an internal helical conveyor for solids removal (herein called a decanter centrifuge) separated the sludge into two fractions substantially different in composition. The primary constituent of the sludge was calcium carbonate, with lesser amounts of magnesium phosphate, calcium hydroxyapatite, and organic solids. Evans *et al.* [3] found that the calcium carbonate was concentrated in the solids in the cake, whereas the magnesium and phosphate compounds were concentrated in the solids in the centrate. Consequently, instead of just wasting a portion of the cake to bleed off impurities, they deliberately operated their centrifuge inefficiently, losing the undesirable phosphates and magnesium compounds in the centrate. The cake, which was enriched in calcium carbonate, was reburned to CaO and reused. The centrate solids were subsequently collected by a second centrifuge using a polymer and discarded. This procedure improved the economics of their process because the lime concentration in the reburned product was increased, calcium carbonate losses were lower, and lime makeup was reduced.

Parker *et al.* [*4*] reported results of a similar investigation with a sludge produced by treatment of raw wastewater with lime. Organic solids were much higher in the sludge than were observed by Evans *et al.* Nevertheless, a similar degree of classification of recoverable calcium into the centrifuge cake occurred.

Analysis of information obtained from the Los Angeles County Water Pollution Control Districts (LACWPCD) showed that this effect also occurs with the heavy metals in sewage sludge [*5*]. At the time, the LACWPCD sludge was being centrifuged in a Bird decanter centrifuge without a polymeric conditioning agent. Recoveries of sludge in the cake were poor—on the order of 40 percent. Examination of data showed that concentrations of metals such as cadmium and lead were substantially higher in the centrate solids than in the cake solids.

The interesting results of these investigators suggested that centrifugal classification might prove to be a useful and cost-effective method for removing harmful substances from sewage sludge. Consequently, an investigation of this separation method was commenced at EPA's Municipal Environmental Research Laboratory in Cincinnati. The investigation was divided into three parts. First, published data of other investigators were examined to determine if there was a suitable means of correlating the degree of separation achievable with machine or process variables. Second, a pilot-scale investigation was commenced using sludge from Cincinnati's Mill Creek plant to determine if the LACWPCD classification results could be verified in another sludge, and third, LACWPCD records were investigated to determine whether more unpublished supporting data could be found. Results of these three phases of our investigation are presented in the following sections.

CORRELATION OF CLASSIFICATION RESULTS

The most suitable information available at the time for testing a correlation method was the data of Evans *et al.* [3]. They worked with what was primarily a mineral sludge, which would not be expected to show large variations in characteristics with time. Most important, they obtained classification data over a range of cake recoveries. Cake recovery was varied by varying feed rate to the centrifuge over a limited range. Centrifuge bowl speed and speed of the conveyor for removing solids from the centrifuge were held constant (see below for description of a decanter centrifuge). Pool depth was varied but did not affect classification significantly.

The data obtained by Evans *et al.* have been replotted essentially in the same fashion as presented by these authors and are shown in Figure 1 for recalcinable calcium oxide. Percentage of the recalcinable calcium oxide that is recovered in the cake is plotted against percent of total solids recovered in the cake. The correlation procedure is useful but clearly several data points are required to get an

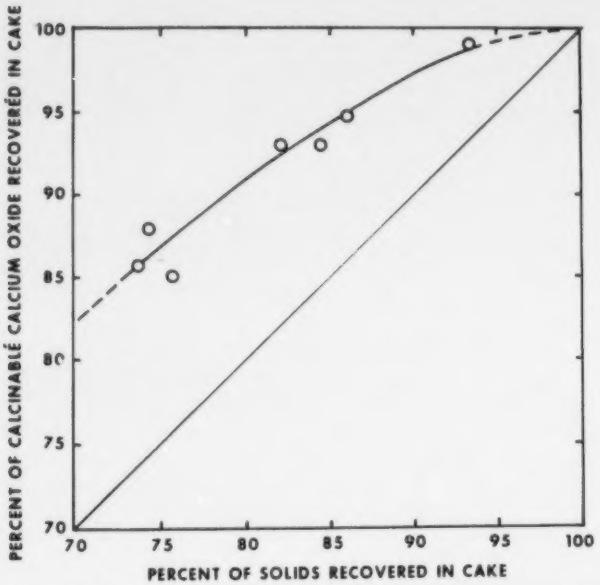


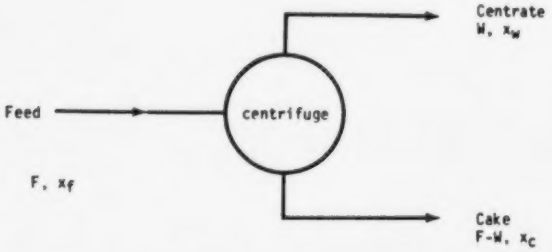
Figure 1. Correlation of recovery of a species (in this case, recalcinable CaO) with total solids recovery in the cake of a decanter centrifuge (from Evans *et al.*).

estimate of trends over a range of recoveries.

The superficial resemblance of the curve in Figure 1 to the familiar x-y diagram used to present vapor-liquid equilibrium data [6] led to the thought that a pseudo-relative volatility would be reasonably constant over a substantial range of recovered solids. The pseudo-relative volatility, called here a "recovery factor" (f_r), is calculated from the recoveries of a species and of total solids. Because for sewage sludge the "recovered" substances were concentrated in the centrate, recoveries in the centrate of solids and the various species of interest rather than recoveries in the cake were used. Nomenclature is shown in Figure 2.

The equation for the recovery factor, by analogy to the expression for relative volatility [6], is given by Equation 1:

$$f_r = \frac{R_a/(1 - R_a)}{R/(1 - R)} \tag{1}$$



F, W, and F-W are mass of suspended solids in feed, centrate, and cake.

x_f, x_w, and x_c are weight fraction (dry solids basis) of a species in the suspended solids in feed, centrate, and cake.

Figure 2. Representation of the centrifuge experiment, identifying the nomenclature for total flows and flows of any particular species into and out of the centrifuge.

where R_a = recovery of species a in centrate, Wx_w/Fx_f
R = recovery of solids in centrate, W/F

Note that if R_a and R were recoveries in the cake, the recovery factor would be the reciprocal of f_r.

When the definitions of recoveries above are substituted into Equation 1 and combined with the material balance for the species around the centrifuge,

$$Fx_f = Wx_w + (F - W)x_c \tag{2}$$

Equation 1 reduces to a very simple form that is frequently useful in calculating f_r:

$$f_r = x_w/x_c \tag{3}$$

Equation 1 has been applied to the data of Evans *et al.* with the results shown in Table 1. Arithmetic average f_r's have been used to calculate the recoveries, R_a, for the three species reported. Except for the three outliers noted, the average f_r's represent the data well, as indicated by the agreement between calculated and measurable recoveries for the three species (column 2 versus column 4 in the table). The range of the total recoveries, R, is substantial (about 8 to 26 percent) but evaluation over a broader range would clearly be desirable.

The correlation approach used, if proven to be sufficiently general and usable over a broad range of recoveries, can greatly simplify collection of screening data to determine the value of centrifuged classification for a desired separation. Instead of establishing an entire recovery curve (e.g., Figure 1), it may be adequate to determine as few as one or two experimental points to indicate the utility of the approach. This potential was kept in mind in planning the experimental phase of the investigation.

PILOT-SCALE STUDIES WITH SEWAGE SLUDGE

Objectives

The objectives of this phase of the investigation were to establish the extent of classification that occurs in sewage sludge for a variety of trace metals, determine the

TABLE 1. COMPARISON OF MEASURED AND CALCULATED RECOVERIES
(Evans *et al.*'s Data)

Species	Experimental Data R	Experimental Data Ra	Calculated f_r	R_a, Calcd. from f_r-av.
PO_4	0.24	0.90	27.8[1]	—
	0.18	0.31	2.1	0.30
	0.16	0.29	2.2	0.27
	0.08	0.14	1.9	0.15
	0.07	0.11	1.7	0.13
			1.98 Ave.	
Mg	0.18	0.31	2.0	0.31
	0.16	0.29	2.2	0.28
	0.07	0.12	2.0	0.13
	0.08	0.04	0.5[1]	—
			2.07 Ave.	
Ca	0.24	0.15	0.55	0.12
	0.26	0.14	0.47	0.13
	0.26	0.12	0.40	0.13
	0.14	0.05	0.34	0.06
	0.16	0.07	0.42	0.07
	0.18	0.07	0.36	0.085
	0.08	0.01	0.14[1]	—
			0.42 Ave.	

[1] Outliers, not used in calculation of average f_r's.

influence of the operating parameters of the centrifuge, and verify that the data obtained could be correlated over a broad range of variables by use of the "recovery factor" parameters.

Materials and Methods

A pilot-scale decanter centrifuge (Sharples Model P-660, 0.15 m diam.), installed at the EPA's Test and Evaluation Facility at Cincinnati's Mill Creek Sewage Treatment Plant, was used for this investigation. Mill Creek's undigested primary sludge was used for all experiments. Composition range of heavy metals in this sludge during the experimental program is shown in Table 2. The wastewater has a substantial industrial contribution, but metals concentrations are not unusually high. Variables investigated were centrifuge bowl speed (RPM), depth of the liquid pool in the centrifuge bowl (PD), differential speed between bowl and conveyor (DELTA), and sludge feed rate (GPM). All other machine variables and sludge properties were held as constant as possible. A schematic drawing of a decanter centrifuge is shown in Figure 3. The centrifuge tested was a countercurrent flow machine—the solids thrown against the inner wall of the bowl were moved by the conveyor opposite to the direction of the liquid flow.

The feed sludge for the experiments was prethickened to about 2-4 percent solids, and screened to remove particles that might clog openings in the small decanter centrifuge. The screened sludge was stored in a 30.3-m^3 tank and was mixed with an air sparger to produce a uniform composition and prevent septicity. The tank contents provided the material for a day's operation, about 6-8 runs. No new sludge was added to the tank during an operating day. Input flow to the centrifuge passed through a grinder and a magnetic flow meter. No conditioning agents to improve particle collection were used. A schematic diagram of the sludge feeding system is shown in Figure 4.

To commence a run, the centrifuge was operated at the desired conditions for about 15 minutes to achieve steady state. Then the test period of about 5 to 15 minutes commenced, during which time all cake and centrate were collected. Samples of the cake and centrate were taken for determination of concentration of total solids and the following metals: cadmium, lead, zinc, copper, nickel, calcium, and iron. Sludge samples were digested with nitric/perchloric acid as has been described elsewhere [7] and metals concentrations were determined by atomic absorption spectrophotometry.

Balances for total mass and for individual metals were carried out. Material balance results for Experiment 1 (see below) are shown in Table 3. Material balances were good for total mass and total solids. Material balance for metals showed substantial variability, even though each measurement of a solids composition was an average of four or more grab samples. Metals analyses were conducted on composited samples. The relatively high standard deviations of the ratio of output to input for the metals indicate

TABLE 2. CONCENTRATIONS OF HEAVY METALS IN CINCINNATI'S MILL CREEK RAW PRIMARY SLUDGE DURING CENTRIFUGATION EXPERIMENTS

	Concentrations (mg/kg, dry solids basis)		
	Low	High	Median
Cadmium	12	81	38
Lead	130	731	476
Copper	1,390	2,280	1,510
Nickel	240	680	380
Zinc	900	1,600	1,390
Calcium	8,400	28,900	14,100
Iron	11,600	21,600	15,300

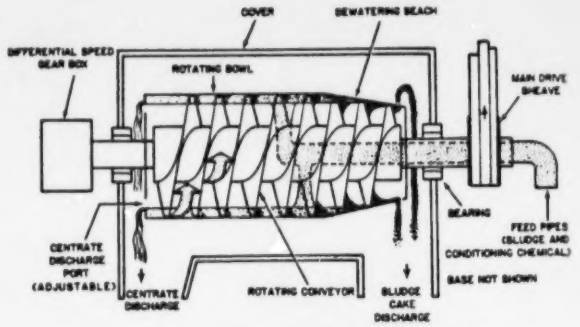


Figure 3. Continuous countercurrent solid bowl centrifuge.

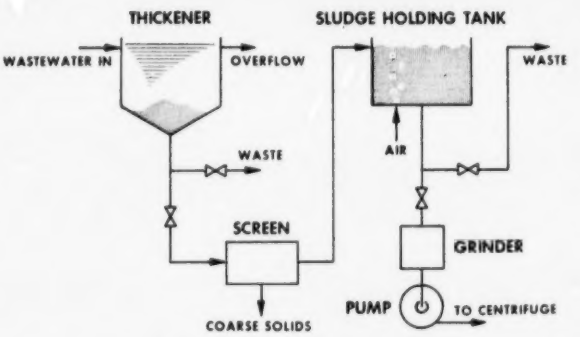


Figure 4. Sludge feeding system.

that compositions were fluctuating or that insufficient time was allowed for arriving at steady state. To eliminate the latter possibility, future experiments should use longer time periods to achieve steady state, and the sample collection period at steady state should be longer.

The effect of the poor material balances for some of the metals on the results is not certain. The calculations of f_r were made by Equation 3, which only uses the output compositions; consequently, variations in f_r might not reflect the uncertainty in the material balances. The consistency of the results (see below) indicates that the results are actually better than the material balances might indicate.

Experimental Design

For maximum efficiency, the experiments conducted with the centrifuge were factorial designs [8]. Experiment No. 1 was planned as a 3 × 2 × 2 × 2 factorial experiment (three bowl speeds, two pool depths, two differential

TABLE 3. AVERAGE AND STANDARD DEVIATION(S) FOR THE RATIO OF MASS OUTPUT TO INPUT (O/I) FOR CENTRIFUGE EXPERIMENTS

No. of Measurements	Experiment 1		Experiment 2		All Experiments	
	40		24		83	
	Ave O/I	s	Ave O/I	s	Ave O/I	s
Total Mass					0.96	0.045
Total Solids					0.91	0.14
Elements*						
Cd	1.05(2)	0.28	0.89(1)	0.21		
Pb	1.14	0.29	0.97(2)	0.38		
Zn	0.98	0.25	0.95(1)	0.18		
Cu	0.99	0.17	0.99(2)	0.22		
Ni	1.00	0.15	1.01(1)	0.18		
Ca	1.00	0.24	1.03(2)	0.29		
Fe	0.99	0.16	1.11(2)	0.26		

*( ) indicates number of outliers not included in the average.

speeds, and two flow rates) replicated once. This large experiment necessarily extended over a period of many days. Procedures were followed which attempted to minimize the expected variations in sludge composition. The procedures for collecting sludge feed outlined in the preceding section were followed, which maintained sludge composition and quality constant during a single day. A complete block of tests, comprising a replicated 2 × 2 sub-experiment (differential speed × flow rate), was then run in a single day. As soon as possible (but not the same day), another sub-experiment was conducted at the second pool depth. Finally, this subset, now a 2 × 2 × 2 experiment, was repeated for each of the two remaining bowl speeds. Unfortunately, examination of the data leads to the conclusion that the effects of pool depth and bowl speed are confused with day-to-day changes in sludge and cannot be evaluated. The centrifuge machine settings and sludge feed conditions for this experiment are presented in Table 4.

In order to test the effect of bowl speed on the same sludge, the centrifuge was modified by installation of a variable speed drive, which permitted quick changes in bowl speed. A second factorial experiment (Experiment 2) using the same variables as before (two pool depths, two differential speeds, three bowl speeds, and two feed rates) was carried out except that there were no replicates. On a single day, six runs could be made, varying bowl speed and flow rate, at fixed differential speed and fixed pool depth. Then, these six runs were repeated on another day at the second differential speed. The two sets of six runs were then repeated at a new pool depth. Machine and sludge feed conditions are shown in Table 4. Because pool depth and differential speed were held constant during a day, their effects are confused with day-to-day changes in the sludge.

A third set of experiments designed to establish the response surface for the operating variables was in progress when the gear train of the centrifuge was damaged, terminating all further experiments. Unfortunately, experiments in which the effect of pool depth was determined on the same sludge were never run. However, cumulative information from the three sets of experiments presents a reasonable picture of effect of variables on classification of metals.

Analysis of Experimental Results

Interpretation of Normalized Data. As noted earlier, experimentation soon showed that day-to-day variation in the sludge was substantial. Comparison of results obtained on different days were thus confounded with random unknown effects of changes in sludge characteristics. To allow interpretation of Experiments 1 and 2 in their entirety, each day's results, which were complete sub-experiments, have been normalized by calculating f_r, for each test, calculating an arithmetic average f_r, and normalizing by dividing each f_r by the average. Normalized f_r's are indicated by the symbol $n - f_r$. Naturally, the overall average of the normalized f_r's for a day's tests must equal unity; thus, any variables that did not vary within a day (bowl speed and pool depth for Experiment 1, differential speed and pool depth for Experiment 2) show zero effects, although their interactions with other variables are not zero.

Effects of variables and interactions on f_r determined from results of Experiment 1 are presented in Table 5. Increase in flow rate (GPM) increases f_r for all but one metal and the increase is statistically significant for Cd and Ca. Differential speed (DELTA) effects are small and fluctuate in direction, indicating only random error. The effect of pool depth (PD) is unknown but its interaction with flow rate appears to be important—it is substantially significant for three metals. A high pool depth reduces the improvement in f_r produced by increased feed rate. The nature of this interaction suggests that a combined variable, PD/GPM, which is proportional to time of exposure of sludge to the centrifugal field, might be appropriate.

Results of Experiment 2 are presented in Table 6. Data have been normalized as for Experiment 1. Increasing centrifuge speed (RPM) increases $n - f_r$ significantly for Cd and Pb, but the effect is much less and not significant for other metals. Flow rate (GPM) effect is substantial and quite similar to results obtained for Experiment 1.

Significant interactions did not follow any regular pattern in Experiment 2. In one case, the PD × GPM interaction was significant and in the same direction as for Experiment 1. Average f_r's are lower in Experiment 2 than in Experiment 1. A difference is to be expected because the experiments were run nearly a month apart.

In the experiments, significant effects occur more frequently for metals showing the most classification into the centrate (Cd and Pb) and into the cake (Ca). This behavior is reasonable. If, for example, a metal is only slightly classified, as indicated by an f_r near unity, no appreciable effect of machine variables on f_r should be anticipated.

The results of the factorial analysis show that the use of the recovery factor is an extremely useful tool for correlation centrifugal classification results. Results can be expressed by a single parameter, f_r, which is only slightly affected by the operating conditions of the centrifuge.

TABLE 4. MACHINE AND SLUDGE FEED CONDITIONS FOR EXPERIMENT 1 (5/29-7/22) AND EXPERIMENT 2 (8/13-8/28)

		Machine Conditions				Feed Conditions	
Date	Replications/ Tests	Speed (1000 RPM)	Pool Depth	Differential Speed	Flow Rate** (GPM)	Solids Content (%)	Range of Total Solids Recoveries
				Experiment 1			
5/29	2/8	5.0	1	Min., Max.	2, 5	1.28	0.33-0.50
6/3	2/8	5.0	4	Min., Max.	2, 5	2.38	0.22-0.50
6/9	2/8	3.1	4	Min., Max.	2, 5	1.27	0.29-0.54
6/11	2/8	3.1	1	Min., Max.	2, 5	1.85	0.30-0.60
7/17	2/8	1.9	1	Min., Max.	2, 5	2.93	0.52-0.82
7/22	2/8	1.9	4	Min., Max.	2, 5	2.34	0.35-0.58
				Experiment 2			
7/29*	1/6	1.9, 3.1, 5	1	L	2, 6	2.25	0.52-0.80
8/13	1/6	1.9, 3.1, 5	1	L	2, 5	2.34	0.38-0.65
8/20	1/6	1.9, 3.1, 5	1	H	2, 5	1.78	0.35-0.80
8/26	1/6	1.9, 3.1, 5	4	L	2, 5	1.55	0.16-0.68
8/28	1/6	1.9, 3 1, 5	4	H	2, 5	1.88	0.19-0.56

* The 7/29 run was incomplete. It was not used to compute the results of the factorial experiment.
** S.I. Conversion: GPM × 0.0631 = LPS (liters/sec).

TABLE 5. EFFECT OF MACHINE VARIABLES ON RECOVERY FACTOR — EXPERIMENT 1

Metal	Average f_r	Magnitude of Effects on Normalized f_r: Main Effects, Delta	Main Effects, GPM	Two Factor Interactions**, PD × GPM
Cd	2.77	−0.06	0.24*	−0.15*
Pb	2.90	0.04	0.08	−0.22*
Cu	1.86	−0.07	0.04	—
Ni	1.60	−0.09	0.08	—
Zn	1.80	−0.03	0.08	—
Ca	0.96	−0.06	0.17*	−0.21*
Fe	1.02	0.14	−0.03	—

* Effect was significant at 95% level or greater.
** Only significant interactions are shown.

Graphical Interpretation of Data. Statistical analysis of the factorial experiments is a very powerful help in analysis, but comprehension is aided when the data can be presented graphically. Fortunately, the data can be illustrated graphically in a way that proves to give confidence in the use of f_r as a correlating parameter. The definition of f_r suggests that, if Equation 1 fits the data, a straight line through the origin will be obtained if $R_n/(1 - R_n)$ is plotted against $R/(1 - R)$. These plots are illustrated in Figure 5 using a portion of the data obtained for cadmium in Experiment 1. The raw data before normalization have been used. The three sets of curves show that straight lines represent the data well, indicating that the assumption of a constant f_r is not unreasonable. The effect of flow rate (GPM) discovered in the factorial analysis (see Table 5) is not apparent in these diagrams. The residual error causes enough variation to obscure the effect of flow rate. The normalized standard deviation in Experiment 1 for cadmium was 0.22. This means that there is a large scatter in the data—about 32 percent of measurements of $n - f_r$ would be expected to fall outside of the one sigma range of ± 0.22. It is easy to see why the normalized effect of flow rate, 0.23, could go unobserved without the factorial analysis. It was only because the large experiment (Experiment 1 contained 24 runs) reduced the residual error to a low value so that the machine variable effects could be seen.

Recovery factors determined as slopes of least square lines of the daily test data, plotted as $R_n/(1 - R_n)$ vs. $R/(1 - R)$, were calculated for all of the tests for all of the metals. These results are shown in Table 7. The values of f_r for each metal fluctuate substantially with time. The major part of this fluctuation was probably due to changes in the sludge, although changes in the centrifuge, such as wear on the helical conveyor for removing sludge, could account for some of the changes.

Data Needed to Predict Degree of Classification. If it is desired to test whether centrifugal separation offers any advantage for separating components of a slurry, the large standard deviations such as experienced in our work make it difficult to make accurate predictions, but simplify the experimental task. Our experiments show that effects of machine variables, although measurable in some cases, are not large compared to the experimental inaccuracy in determining f_r. Similarly, marked changes in f_r appear not to occur as R changes (see Figure 5). Consequently, to get a reasonable estimate of f_r, a few runs can be made, changing a few adjustments in machine variables and feed rate to bracket the desired R, and an average value and standard deviation in the f_r determined. A very large experiment is needed to define the relatively small effects of machine variables. At least for a non-consistent feedstock such as sewage sludge, the relatively large changes in f_r that occur with time make it pointless to excessively refine the estimate of f_r.

LONG TERM EXPERIENCE AT LOS ANGELES

As noted earlier, the LACWPCD had been operating decanter centrifuges for a number of years without using polymers to enhance particle collection, and differences in concentrations of metals in centrate and cake had been observed. The correlation method developed here (use of f_r) allows interpretation of the data and allows a comparison of data collected over a period of years.

The Los Angeles County data are from 1979 and earlier, at which time sludge was centrifuged in a Bird decanter centrifuge and the centrate was again centrifuged in solid-bowl basket-type centrifuges. Because no polymer was used in the decanter centrifuge and recovery of solids was poor, the second centrifugation was needed for efficient solids removal. Data are shown in Table 8, which gives composition of sludge feed, decanter centrifuge cake, and basket centrifuge cake. If it is assumed that all of the sludge solids in the centrate are removed in the basket centrifuge, it is possible to calculate fraction of solids recovered and a recovery factor for the elements and compounds listed in the table. The calculated recoveries scatter but indicate recoveries in the cake of 23 to 30 percent (77 to 70 percent solids are "recovered" in the centrate). The calculated separation factors are substantial for some metals (e.g., 4.5 for cadmium) and for the organic compounds listed. Actually, it was these data that encouraged us to believe that the separation achieved by Evans *et al.* [3] with tertiary slime sludge might occur with sewage sludge.

The Los Angeles County data, which were obtained on digested sludge, indicate better separations for most met-

TABLE 6. EFFECT OF MACHINE VARIABLES ON RECOVERY FACTOR — EXPERIMENT 2

Metal	Average f_r	Magnitude of Effects on Normalized f_r: Main Effects, GPM	Main Effects, RPM (1 to 3)	Two-Factor Interactions**, Delta × GPM	PD × GPM	GPM × RPM (1-2)
Cd	1.86	0.23*	0.28*	—	—	—
Pb	1.77	0.01	0.68*	−0.31	—	—
Cu	1.82	0.17	0.10	—	—	—
Ni	1.48	0.12	0.03	—	—	—
Zn	1.56	0.16*	0.05	—	—	0.26
Ca	0.83	0.40*	−0.06	—	−0.26	—
Fe	1.37	0.24*	0.16	—	—	—

* Effect was significant at 95% level or greater.
** Only significant interactions are shown.

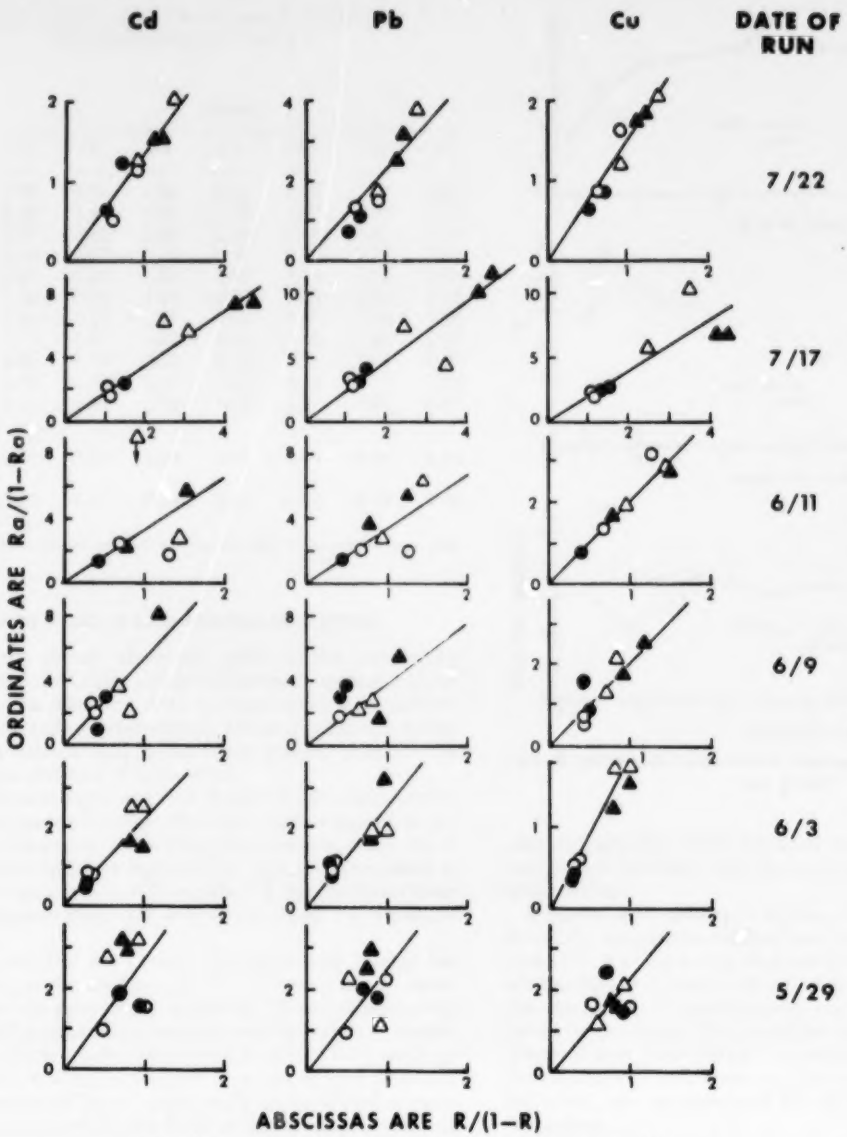


Figure 5. Comparison of Ra/(1-Ra) to R/(1-R) for cadmium, lead and copper (symbols: 0 = 2gpm, Δ = 5 gpm; unshaded = low Delta, shaded = high Delta).

als than were obtained in the present investigation of raw undigested sludge, but were poorer for others, particularly for lead. The relative magnitudes of the f_r's calculated from this study and from the Los Angeles data collected over about two years are given below:

	Cd	>	Zn	>	Ni	>	Cu	>	Pb
L.A.	(3.6)		(2.9)		(2.6)		(2.2)		(0.8)
	Pb	>	Cd	>	Cu	>	Zn	>	Ni
This Study	(3.2)		(2.8)		(1.9)		(1.8)		(1.7)

The differences in magnitude and relative position are substantial but not unexpected. Industrial mix of the two cities is different so the sources of the metals in the sludges differ. Los Angeles has a separate system whereas Cincinnati has a combined system (sewage contains storm runoff), the Cincinnati sludge was raw and Los Angeles' was digested. It can be said that most of the heavy metals will be classified into the centrate, but magnitude and relative position will have to be established by experiment.

Data in Table 8 show that organic substances such as pesticides and PCB's are classified into the centrate. This is an interesting and highly desirable occurrence. In other separation techniques such as extraction, it would be expected that two extractions would be needed to remove metals and organic chemicals: an aqueous acid extraction for metals and an organic solvent extraction for the organic compounds. Centrifugal classification evidently removes a large portion of both in a single step.

One extremely important question is the reproducibility of the phenomena. Our data indicate substantial fluctuations with time (Table 7). Fortunately, Los Angeles has also provided us with long term data [9] from which f_r's could be calculated that indicate surprising consistency with time. These data were provided in the form shown in Table 8 and recovery factors were calculated in the same manner as shown in the table. Monthly values of f_r for cadmium over the three-year period are plotted in Figure 6. Means and standard deviation of f_r's are shown on the figure. There are no trends that indicate low recovery factors for long periods of time. Standard deviations are not excessive. Similar experience would likely be encountered in other citites, barring some drastic change in the industrial mix.

TABLE 7. CALCULATED RECOVERY FACTORS (f_r) FOR EXPERIMENTS 1 AND 2

Date of Run	Metal						
	Cd	Pb	Zn	Cu	Ni	Ca	Fe
5/29	2.78	2.50	1.60	2.12	1.74	1.94	0.92
6/3	2.22	2.48	1.58	1.72	1.57	0.50	0.95
6/9	5.27	3.82	2.07	2.16	1.48	0.91	1.04
6/11	3.30	3.27	2.12	2.03	1.52	0.79	0.84
7/17	2.07	2.27	1.59	1.88	1.36	0.78	0.90
7/22	1.36	2.25	1.76	1.51	1.76	0.81	1.12
7/29*	1.86	5.10	1.77	1.91	1.77	1.06	1.05
8/13	2.73	1.87	1.92	2.34	1.89	1.53	1.98
8/20	2.05	1.10	1.27	1.75	1.15	1.23	1.76
8/26	1.49	2.50	1.47	1.53	1.44	0.73	1.02
8/28	1.41	1.01	1.29	1.58	1.27	0.51	0.67
Arithmetic Average	2.41	2.56	1.68	1.78	1.54	0.98	1.11
Std. Deviation	1.13	1.17	0.28	0.41	0.23	0.44	0.40

* This experiment was not complete and was not used in the factorial experiment calculations.

DISCUSSION OF RESULTS AND PROCESS POTENTIAL

The results clearly show the value of the correlating method developed. The utility of the recovery factor, f_r, in correlating classification data is impressive. A minimum of data is needed to determine f_r. Once it is known, material balance calculations can be made quickly to assess the utility of the method of separation.

The method is empirical and should not be extrapolated over a wide range of compositions or a wide range of recoveries. It can be demonstrated that, for example, at a f_r of 3.0, which is reasonable in light of the values determined in the above experiments, if R equals 0.5, impossible values of x_w (i.e., greater than one) will be obtained if x_f is greater than 0.667.

The potential of the process for upgrading sludge has one handicap—the sludge cake is reduced in heavy metal content, and the centrate is increased. The situation would be better if the cake solids were increased in heavy metals and the centrate solids reduced in metals. Then, an obvious application would be ocean disposal or land disposal. A small amount of "dirty" cake could be landfilled or carefully incinerated while the bulk of the centrate, probably after thickening, could be used on the land or disposed with much less than half the environmental impact of the total sludge.

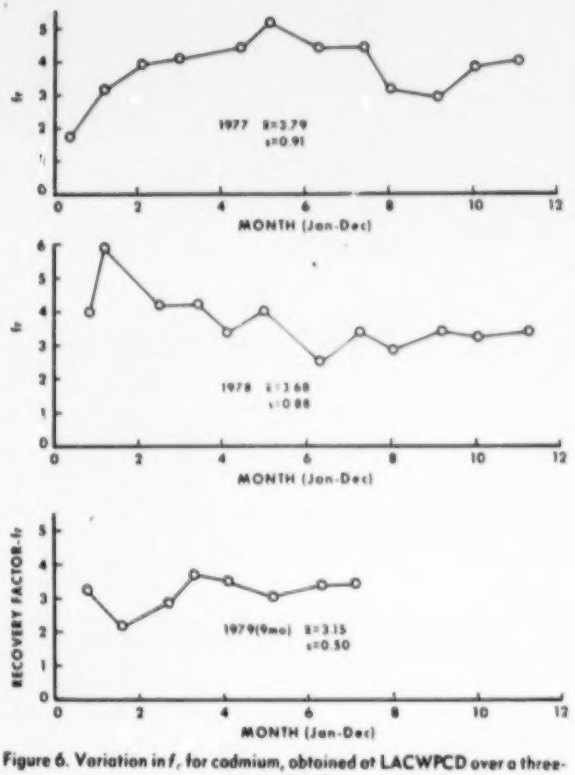


Figure 6. Variation in f_r for cadmium, obtained at LACWPCD over a three-year period.

Despite the handicap, it appears that cost-effective ways to use the separation method can be devised. One application is in a plant using dedicated disposal to get rid of a sludge higher in metals than is suitable for use on land. If the sludge were centrifugally classified, a "clean" cake could be produced that could be used on farmland at low disposal cost. The "dirty" centrate could be disposed to the dedicated land. Since organic loading would be much reduced, the capacity of the disposal site would be increased.

TABLE 8. CLASSIFICATION OF METALS AND ORGANIC COMPOUNDS BY DECANTER CENTRIFUGES AT LOS ANGELES COUNTY (AUGUST 1977)

	Concentrations (mg/kg dry solids)[1]				
	Decanter feed (x_f)	Decanter cake (x_c)	Basket cake (x_w)	Calculated Recovery of Solids in Cake	f_c ($= x_w/x_c$)
As	23	9	25	0.12	2.8
Hg	7	6	7	0	1.2
Ag	42	19	49	0.23	2.6
Cd	59	16	72	0.23	4.5
Ni	400	170	460	0.21	2.7
Pb	980	1500	1300	<0	0.86
Cr	2000	570	2600	0.30	4.6
Cu	1200	520	1400	0.23	2.7
Zn	3400	1100	4400	0.30	4
DDT	12	3	9.3	<0	3.1
PCB	8.5	2.3	7.7	<0	3.3
ALL					
All Pesticides	12	3	9.3	<0	3.1
TICH[2]	19.5	5.5	17.0	0.3	3.1

[1] Symbols correspond to nomenclature in Figure 2.
[2] TICH-Total identifiable chlorinated hydrocarbons.

Another potential application is for a community which would like to compost its sludge but which has a sludge with a high metals content. The cake could be upgraded by centrifugation and the centrate thickened and dried in lagoons for ultimate disposal in a landfill.

In principle, countercurrent staging would allow production of an ultra-clean cake and an ultra-dirty centrate. Unfortunately a stage would compromise a centrifuge and a mixer for reconstituting cake to a slurry. It is unlikely that the net reduction in cost of disposal would offset the cost of the added capital and operating expense of such a system.

CONCLUSIONS AND RECOMMENDATIONS

Significant conclusions are as follows:

1) Data for centrifugal classification appear to be suitably correlated by an easily calculated recovery factor, which in principle can be calculated from a single data point. The factor is a function of machine settings but an average recovery factor can be used to predict recoveries of a specific element with reasonable accuracy. The recovery factor can be extrapolated over a modest range of metal concentrations and recoveries. Substantial random error is to be expected so a sufficient number of runs should be made to establish the standard error of the recovery factor.
2) The degree of classification as indicated by the recovery factor, f_r, is better at high sludge feed rate and high centrifuge speeds. The differential speed of the internal conveyor does not seem to be an important variable. The effect of pool depth was confounded with day-to-day variations in the sludge so it could not be determined. However, interactions of pool depth with sludge feed rate indicate that pool depth divided by feed rate, which is proportional to time in the centrifuge, is an important variable.
3) The degree of classification, f_r, for a metal fluctuates with time. However, data collected over a three year period at Los Angeles indicate that the degree of classificatin does not undergo serious changes in magnitude with time.
4) The selectivity of the method for separating desirable from undesirable substances is good. Most of the heavy metals as well as toxic organic compounds are classified into the centrate. The results obtained show encouraging possibilities for centrifugal classification of sludges.

Recommendations for future work are as follows:

1) Attempts should be made to relate the design parameters of centrifugees (e.g., concurrent *vs.* countercurrent flow; long bowl *vs.* short bowl) to the degree of separation achieved. It is very unlikely that the centrifuge used in these experiments is the optimum design. Investigation of several designs should be made. From the differences in performance observed, the characteristics that improve separation can be identified and an optimized design can be selected.
2) More work should be done with a variety of different sludges, particularly on sludges with high proportion of toxic organic compounds. The Los Angeles data show substantial classification but more supporting information is needed.
3) Chemical and mineral processing industries should give serious consideration to centrifugal classification as a relatively inexpensive unit operation that could reduce waste of valuable materials in spent slurries.

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